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DAMAGE ASSESSMENT IN STRUCTURES USING VIBRATION DATA AND SMART MATERIALS

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ABSTRACT

This paper addresses about the condition monitoring and damage detection of structural beams by using model based techniques. In this work, a technique for programmed crack recognition as well as localization is exhibited. The structure is thought to be placed with actuators as well as sensors to vibrate and captures its dynamic reaction, includes impacts of vibration. In vibrational appeal, the information incorporates the modal reactions of the structure actuator previously, also after the crack. In order to locate the structure based damage, an element of the structure is taken for simulation, the damage in the structure is simulated by varying the stiffness of the element accordingly. The severity and location of unknown defects are judged closely using damage index (DI) which is calculated from the Frequency Response Function (FRF) is used to indicate the severity and location of the crack by judging closely by Damage Index (DI). The contrasts between dynamical properties in the damaged and undamaged structures give the estimation of Damage Index (DI). This methodology is applied to simple beam and plate with reduced local stiffness. The potential techniques for practical application condition monitoring problems are discussed.

KEYWORDS: Damage Detection, Condition Monitoring, Piezoelectric Sensors, Frequency Response Function & Damage Index

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Original Article

INTRODUCTION

The main theme in this paper is to locate and characterize the level of damage in structures like a cantilever beam by making use of smart piezo materials and which are utilized as a part of developing a number of commercial applications, for example, aviation, machine-apparatus and car organizations. The few changes in natural frequencies can be observed while measuring the vibration response when the damage is located in the structure [1, 2]. Diaz and suites [3] who is a pioneer in enhancing a condition, observing framework and the impact of dissemination on the modular frequencies of overlaid composite layers has been examined. Vibration is created from a linear source of frequency, a piezoelectric component with a linear range of frequency is utilized to deliver vibration on the structure and its reaction recorded through piezoelectric film sensors. Reaves and Horta [4] provide a set of benchmark test articles by using commercially available finite element analysis packages to examine techniques for modeling structures containing piezoelectric sensors. Improper bounding of actuators greatly affects the electrical to mechanical effectiveness of the actuator which will lead to anti-resonance. The extensive use of a piezoelectric inertial actuator attached to a structure as a collocated sensor with actuator for monitoring the integrity of the structure provided by by Ling and Xie [5].

Later Staszewski [6] gave the significance of insightful signal processing for crack recognition in

composite structures utilizing distinctive observing procedures. A method by Warden and Manson [7] is viewed as a Level I based diagnostic idea of the possibility of crack recognition. At the point, when damage emerges among two sensors, stiffness amongst the sensors will get influenced and this causes the neighborhood vibration reaction at high frequencies as shown by Mickens et.al [8]. At Work is completed to create reasonable non-intrusive dynamic sensors that can be put on the current maturing aviation structures for observing the onset and advance of basic harm (endurance and erosion) has been displayed by Giurgiutiu and Redmond [9]. Ribeoro et.al [10]. Explored numerically utilizing finite component, demonstrate conditions of the structure and the fortified piezo electric material by using the mechanical vitality of structural and electrical vitality of piezo electric structure. Sumant and Maiti [11] proposed a strategy to distinguish the size and area of an edge typical crack in a component like beam by settling discrete PZT patches at its top and base edges. Both the results, theoretical and experimental are presented

Despite extensive studies on vibration analysis of damaged structures, only a few effective and practical techniques are found for damage identification. This paper, therefore, focuses on the study of localized changes in stiffness results, thus in quantifying Damage Index (DI) based on FRF's changes as a possible method for damage detection purposes for beam and plate structures.

Introduction to Pzt Materials

Definition

When some quantified mechanical strain is applied to a material, produces an electrical charge, which is termed as piezo-electricity. Due to input electrical field reaction, dimensional change in a material or strain production termed as an inverse effect of piezo-electricity. A property that has the piezo electric principled nature manifests the behavior of both piezoelectric and inverse piezoelectric. Piezoelectricity allows exchange of electrical and mechanical energy in a linear reversible phenomenon manner.

Piezoelectric Materials

Naturally occurring materials that are quartz, tourmaline, Rochelle salt display property of piezoelectricity. Apart from naturally occurring piezoelectric crystals, there are few men made ceramic materials such as barium-titanate ($BaTiO3$), lead-zirconate ($PbZrO3$), lead-titanate ($PbTiO2$), lead-zirconate-titanate (PZT), and polymer material such as Poly-vinylidene-Difluoride (PVDF) that could be transformed as piezoelectric material. The man-made piezoelectric materials should undergo a particular process called POLING, to make the material exhibit piezo electric property.

Piezoelectric Actuators

On successful polling procedure completion, positive polarity and negative polarity electrodes are gained by artificial piezoelectric crystals. The voltage generated will have the same polarity as piezoelectric crystal, on compression of piezoelectric material in the direction of polarization in generator-sensor application. When the material, exhibits, tension in the direction of polarization, conducts opposite polarity. The materials expands and contracts in polarization direction and perpendicular direction of polarization respectively, with the application of voltage of same polarity in motor/actuator mode. The materials contracts and expands in polarization direction and perpendicular direction of polarization respectively on the application of voltage of inverse polarity in motor/actuator mode. Piezoelectric actuators exhibit different properties which cannot be produced by other materials such piezoelectric constants, higher permittivity, larger dielectric constants, higher dielectric losses, larger electromechanical coupling factors, low mechanical quality

factors, a lower coercive field, and is easier to depolarize larger,

The numerical value of strain induced in the material is directly proportional to the electric charge on the material. The added disadvantage for piezoelectric systems is their strain in expansion direction, which results in deformation of the unit cell structure. Also, the ability of piezo-electricity is lost, when material works at elevated temperatures, i.e. above the Curie temperature's, at this point the functionality of piezoelectric material will be improper. Every piezoelectric material has a different and distinct Curie temperature. PZT materials are commonly used for its special features, so this is the main reason behind the popularity of piezoelectric materials. Curie temperature of piezoelectric materials lies between 170 to 360oC. The foremost drawback in application wise is, it requires higher voltages (i.e, in the order of hundreds of Volts). However, the requirements current is considerable amount compared to voltages (i.e., in the order of Milli amperes). Due to the low current consumption by PZT's, the required power supply to the piezoelectric materials is reduced. Piezoelectric actuators generally need high voltage piezoelectric amplifiers to employ. When planning a dynamic vibration control framework for an aviation structure outlining of voltage piezoelectric speakers will be an enormous undertaking and an issue due to space confinement. There are a number of forms of piezoelectric sensors in terms of their physical appearance, namely, bimorph actuators, stack actuators, patch actuators, MFC (Macro Fiber Composite) actuators, mechanically amplified stack actuators, piezo tube actuators, special design type sensors and piezo motors. A suitable type of actuator can be picked on the basis of need of force and the strain requirement.

When an electric field is applied between the two electrodes of an actuator then as a result piezoelectric effect is displayed. In order to experience the high intensity of the electric field of piezoelectric material, the material should less in the thickness direction, i.e. between the cathode surfaces ought to be little for a lasting voltage since the recipe for electric field between two plates.

$$E=V/t \tag{1}$$

Where E indicates the electric field amongst the cathodes and it indicates the gap between the anodes. That clarifies why constructing a piezoelectric actuator as a thin plate is favorable.

A general practice in the utilization of this logical reality is the piezoelectric fix actuators. Actuators which are captivated towards the path opposite to the surface and an electric field is connected likewise in their thickness heading. For the most part, the polarized course of a piezoelectric sensor is expressed as pivot number 3, which is the thickness of a Pzt actuator fix. Evidently, we can state that the length and width of the piezoelectric actuator material to be named as pivot 1 and hub 2. At the point, when an electric field is connected towards pivot 3 with the inverse extremity as the piezoelectric actuator packs the piece in hub 3 heading and experience strain compel in hub 1 and hub 2 bearings.

EFFECT OF DAMAGE ON THE MODAL RESPONSE OF A FIXED ENDED BEAM

A good arrangement of work has been done in the investigation and examination of the worldwide element conduct of structures for damage identification of damage purposes [1, 2]. Thinks about have been led to watch the adjustments in the module parameters to identify and portray damage [4-6]. In great adapted structures, for instance, the nearness of a surface break creates an adjustment in the physical properties (e.g., firmness) of structures and furthermore apparently in the module parameters. As the recurrence reaction work (FRF) is a component of such properties, it is on a fundamental level conceivable to identify and restrict the imperfection by ascertaining the adjustments in the recurrence reaction work. The presence of and extent of damage can be obtained by measuring or calculating the frequency response

function of the dynamic response of the structure before and after damage appears. By using undamaged and damaged frequency response functions, dimensionless amount is calculated to locate damage location as well as size is calculated by using. The quantity here is implied to the damage index (DI), and it is a function of the damage level and its vicinity. The essential comprehension behind this crack distinguishing proof technique is spoken to by considering the vibration of a structure called aluminum beam of dimensions 0.35m × 0.015m x 0.003m (l× b× h) with both ends fixed with young's modulus of 70 GPA and a density of 2100 kg/m^3 is used as shown in Figure 1

Table 1: Damage Scenario's with Different Reduction in Stiffness

Damage Scenario	Reduction in Stiffness of Single Element (Damage Severity in %)
Undamaged	0
Case 1	50
Case 2	60
Case 3	80

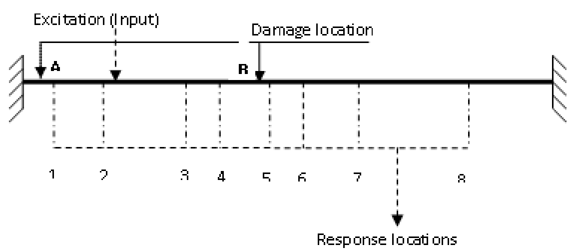


Figure 1: The Excitation Point, Control Points and Damage Locations (A and B) for the Fixed Ended Aluminium Beam

For finite element's purpose, the beam is segregated into 35 two node one-dimensional elements. The response of the beam to applied loads at different response locations 1 to 8 is assessed using the finite element analysis. The crack is simulated by minimizing the Young's Modulus (E) in one element of the beam at each stage of analysis and this simulation is carried out up to three stages. The service related structural degradation is simulated by approximate reduction of stiffness by 50%, 60% and 80% of one element at each and every stage of analysis. Three simulated damage calculations are tabulated in Table 1. A harmonic force of 50N is applied to excite the beam to calculate the frequency response function. At each and every stage of crack percentage level and location, an analysis is conducted for frequency response is performed and the distortion at the control (response) points were redeemed as a function of gene frequencies of first several modes, as shown in Figure 2. It can be seen that even maximum damage case1 negligible effects on the modal frequencies of the beam and variation of the frequencies at the peaks of the frequency response function (FRF's) is smaller. Thus, the task would be difficult to locate the crack in the structure if the modal properties were not used directly. Additionally, more information about the structural conditioning can be achieved if the analysis is completed over the whole scope of frequencies of intrigue

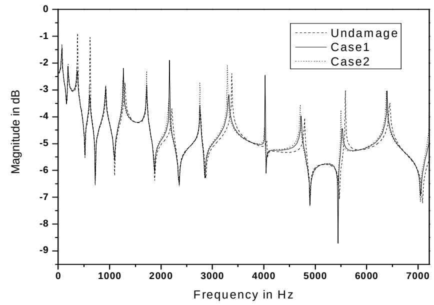
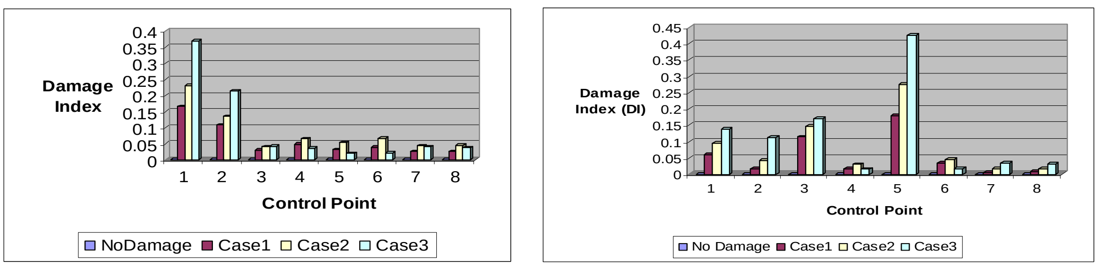


Figure 2: Calculated FRFs at Control Point 5 for Different Cases on the Beam

In order to improvise the viability of the modal proposal, a damage index (DI) is defined by using FRF's of the structure before and after damage Φ_u and Φ_d respectively as root mean square deviation (RMSD).

$$RMSD = \sqrt{\frac{(\Phi_d - \Phi_u)^2}{(\Phi_u)^2}}$$



(3a) **(3b)**

Figure 3: Damage Index for Three Damage Levels (3a) Point A. (3b) Point B

A comparison of the Damage Index for identifying single element damage by using the proposed method is provided in Figure 3 (a and b). The horizontal axis denotes the response locations selected along the length of the beam. The vertical axis denotes the DI at all control points. The value of damage index (DI) for an undamaged structure becomes 'zero', i.e. DL=0 and the damage value will be quantified, when crack exists. Apparently, the estimation of the increments is observed when the contrast between the dynamical reaction of the hand and undamaged structure increments. In the close premises of crack, estimation of crack list indicates higher generally. It is apparent that if the level of crack builds, the estimation of indices additionally increments, and all the more critically, the expansion is much more noticeable at control directs shut toward the damage vicinity.

EFFECT OF DAMAGE ON THE MODAL RESPONSE OF A FIXED ENDED PLATE

The damage index technique is applied next to the fixed ended palette of square cross section of dimension 600mm x 400mm and of 1.5mm thickness, with piezoelectric patches (response points) placed over the selected area of the plate as shown in Figure 4. Material properties considered as Modulus of elasticity are 200 GPA and density 7810 kg/m^3 are used for numerical simulation to evaluate damage index for damage identification and location. Each PZT dimension is 20mm x20mm x 0.5mm. The dynamic behavior is simulated in the ANSYS analysis software. A step wise reduction of

modulus of elasticity is introduced in the present structure and the damage severity is in the range of 50% to 80% for four elements are tabulated. Each and every damage location is observed separately by the value of damage index (DI).

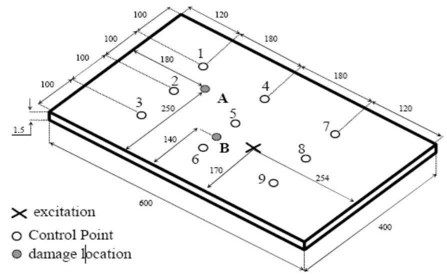


Figure 4: Response (Control) Points, Damage and Excitation Locations for the Aluminium Plate

Finite Element Modeling of Piezoelectrics

As piezo electrics involve interaction between electrical and mechanical fields, they can be modeled using coupled field elements in ANSYS. Vibrational principles are used to develop the finite element equations, which incorporate the piezoelectric effect. SOLID 5element is used for modeling the piezoelectric actuators. The Solid 5 element has a three-dimensional magnetic, thermal, electric, piezoelectric, and structural field capability with limited coupling between the fields. The eight noded element with six degrees of freedom viz., UX, UY, UZ, TEMP, VOLT, and MaG at every node. When used in structural and piezoelectric analyses, SOLID5 has large deflection and stress stiffening capabilities. The input properties for SOLID 5 element are, EX, EY, EZ – modulus of elasticity, N/m^2 in X, Y, and Z directions. NUXY, NUYZ, NUXZ – Poisson's ratio in X, Y, and Z direction, DENS – Mass density, GXY, GYZ – Shear modulus in X and Y directions. The geometry and properties of piezoelectric actuator is used.

Table 2: Properties of Piezoelectric Material (PZT) used as Actuator

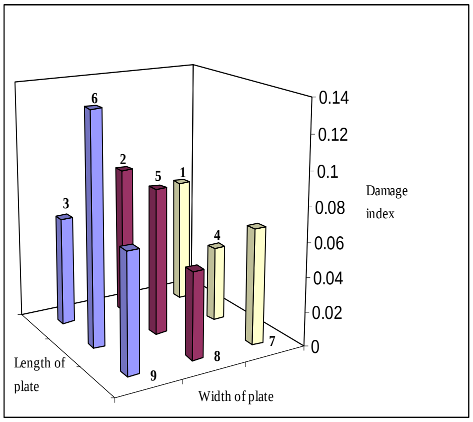
Property	Value
Young's modulus E11, N/m2	63.0e9
Young's modulus E22 and E33 N/m2	63.0e9
Poisson's ratio	0.3
Density, Kg/m3	7800
Piezoelectric charge constant, d31 and d32, m/V or C/N	-179e-12
Piezoelectric charge constant, d33, m/V or C/N	354e-12

Table 3: Simulated Damage Scenarios and Reduction in Stiffness

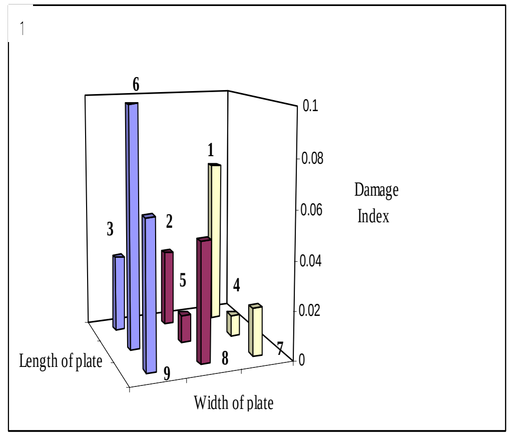
Damage Scenario (Cases)	Number of Elements Damaged	Reduction in Stiffness (Damage Severity)
Case 1	4	80%
Case 2	4	50%
Case 3	4	30%
Case 4 (Damage at two locations)	4 and 4	50%

The value of damage index is calculated by using the calculated value of structure response FRF at every point in the range of frequency of 0 to 300Hz. The results of the simulations for damage location at point B nearer to respond point 6 are shown in Figure 5a, 5b and 5c.

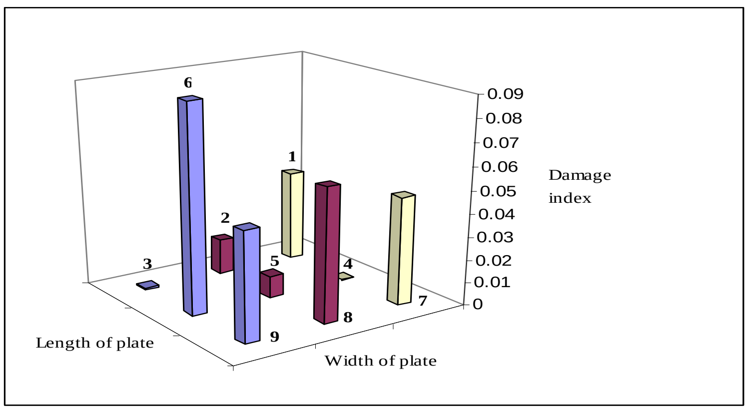
Single Damage Scenarios



(5a)



(5b)



(5c)

Figure 5: Damage Index at Control Points (a) 80% Stiffness Reduction (Case1) (b) 50% Stiffness Reduction (Case2) (c) 30% Stiffness Reduction (Case3)

The Damage Index (DI) values of Frequency Response Function (FRF's) for damage scenario Case1 between the intact and damaged plate. The maximum Damage Index value occurs the at control point 6 in case 1 which is near to the damage location (point B). The same analysis is performed for the other damage scenarios Case2 and Case3 with analogous results obtained. Each plot shows maximum Damage Index value at nearest response point for the chosen the damage location as observed in Figure 5b and 5c. Therefore the present method using Damage index (DI) successfully identifies the position of the damage on plate.

Double Damage Scenarios:

The results of investigation the behavior of Damage Index when two damages at point A and B are induced present in the plate. The same analysis is performed for a plate containing damage two locations. Double damage scenarios of four elements whose 50% stiffness reduction at two locations near 2nd and 6th PZT's are shown as dark points shown in Figure 4.

The increase in Damage index (DI) comparing single damage case (Figure 5, 50%) with DI value for double damage at two locations for 50% loss in stiffness (Figure 6) show additional influence at location 5.

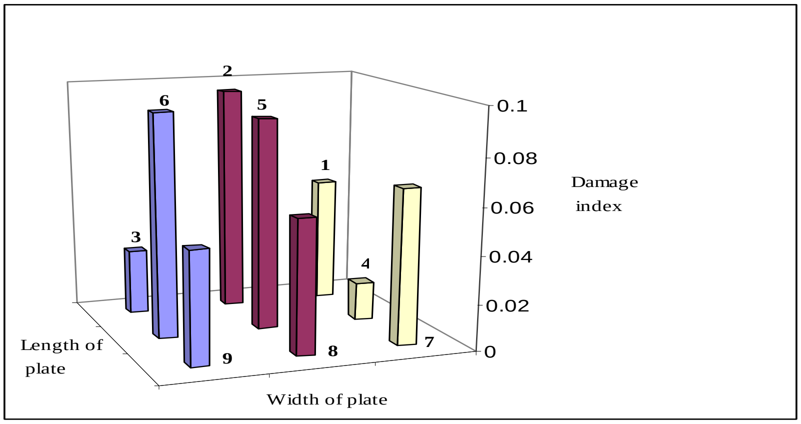


Figure 6: Damage Index DI at Control Points (50% Stiffness Reduction at Two Locations I.E. Case 4)

Which is closer to both damaged location 2 and 6, Therefore the present method using Damage index (DI) successfully identifies the position of the double damages in plate.

CONCLUSIONS

The results show that the frequency response function based damage index method performed well in distinguishing, finding and measuring damages. It is obvious that the lists increment with the level of damage, and all the more imperatively, the response is more pronounced at control (reaction) points in the vicinity of the damage. This method detects damage approximately localize defects in structural components without any user guide intervention. The damage index record approach is capable to fundamentally decrease the time and cost of investigation of extensive structures.

REFERENCES

1. *Doebling S W., and Farrar C R, (1996). "Damage identification and health monitoring of structural and mechanical Systems from changes in their vibration characteristics: A literature review, Research Rep. No. LA-13070-MS, ESA-EA, Los Alamos,*

2. *S.H. Diaz and C. Soutis, (1998). "Delamination detection in composite laminates variations of their modal characteristics", Journal of sound and vibration, 228, 1-9*

3. *S. H. Diaz Valdes and C. Soutis, (1999) Delamination detection in composites laminates from variations of their modal characteristics. Journal of sound and vibration, 288(1), 1-9,*

4. *M. C. Reaves and L.G. Horta, (2001) "Test case for modeling and validation of structures with piezoelectric actuators". AIAA-2001-1466, NASA Langley research center, Hamton, Virginio.*

5. *S.F. Ling and Y. Xie, (2001) "Monitoring structural integrity using a piezoelectric inertial actuator cum sensor', Journal of sound and vibration, 247(4), 731-737,*

6. *W. J. Staszewski, (2002) "Intelligent signal processing for damage detection in composite materials". Journal of composites science and technology. 62, 941-950.*

7. *K. Worden and G. Manson, (2003), "Experimental validation of a structural health monitoring; Part-1. Novelty detection on a laboratory structure". Journal of sound and vibration, 259(2), 323-342,*

8. *T. Mickens, M. Schulz, M. Sundaresan and A. Ghosal, (2003), "Structural health monitoring of an aircraft joint", Mechanical systems and signal processing, 17(2), 285-303,*

9. *V. Giurgiutiu and J. M. Redmond, (2003) "Active sensors for health monitoring of aging aerospace structures", International journal of condition monitoring and diagnostic engineering management (COMADEM), UK, 1-19.*

10. *J.F. Ribeoro, G. L.C. M. De, and Steffen, (2004) "Finite element modeling of a plate with localized piezoelectric sensors and actuators". Journal of the Braz. Soc. of mech. Sci & Eng, - 26, 117-128,*

11. *P.S. Sumant and S. K. Maiti, (2006) "Crack detection in beam using PZT sensors". Smart materials and structures. 15, 635-703.*